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Predictions for masses of bottom baryons

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ABSTRACT

The recent observation of $\Sigma_b^{\pm}$ (uub and ddb) and Ξ_b^- (dsb) baryons at the Tevatron within 2 MeV of our theoretical predictions provides a strong motivation for applying the same theoretical approach, based on modeling the color hyperfine interaction, to predict the masses of other bottom baryons which might be observed in the foreseeable future. For S-wave qqb states we predict $M(\Omega_b) = 6052.1 \pm 5.6$ MeV, $M(\Omega_b^*) = 6082.8 \pm 5.6$ MeV, and $M(\Xi_b^0) = 5786.7 \pm 3.0$ MeV. For states with one unit of orbital angular momentum between the b quark and the two light quarks we predict $M(\Lambda_{b[1/2]}) = 5929 \pm 2$ MeV, $M(\Lambda_{b[3/2]}) = 5940 \pm 2$ MeV, $M(\Xi_{b[1/2]}) = 6106 \pm 4$ MeV, and $M(\Xi_{b[3/2]}) = 6115 \pm 4$ MeV.

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1 Introduction

There has been noteworthy experimental progress recently in the identification of baryons containing a single b quark. The CDF Collaboration has seen the states $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ [1], while both D0 [2] and CDF [3] have observed the Ξ_b^-.

The constituent quark model has been remarkably successful in predicting the masses of these states [4]-[9]. Most recently the careful accounting for wave function effects in the hyperfine interaction [10] has permitted the prediction of the Ξ_b^- mass within a few MeV of observation.

All predictions need an input for the mass difference $m_b - m_c$ between the b and c quarks. That the value of $m_b - m_c$ obtained from hadrons containing b and c quarks depends upon the flavors of the spectator quarks was noted in Ref. [6] where Table I shows that the value is the same for mesons and baryons not containing strange quarks but different when obtained from B_s and D_s mesons. Some reasons for this difference were noted and the issue still requires further investigation.

The new CDF mass measurement [3] of the baryon Ξ_b^- confirms the prediction [10] which uses the value of $m_b - m_c$ obtained from B_s and D_s meson masses. Therefore in our present analysis we use this value of of $m_b - m_c$, as well as a very close value obtained from the $\Xi_b - \Xi_c$ mass difference. Since these values are about 10 MeV lower than the value obtained [6] from nonstrange hadrons, our predictions are lower than other predictions [5, 7] which use nonstrange hadron masses as inputs.

In this model the mass of a hadron is given by the sum of the constituent quark masses plus the color-hyperfine (HF) interactions:

$$V_{ij}^{HF} = v\frac{\vec{\sigma_i} \cdot \vec{\sigma_j}}{m_i m_j}\langle\delta(r_{ij})\rangle \tag{1}$$

where the m_i is the mass of the i-th constituent quark, σ_i its spin, r_{ij} the distance between the quarks and v is the interaction strength. We shall neglect the mass differences between u and d constituent quarks, writing u to stand for either u or d. All the hadron masses (except the ones given in Sec. 3) are for isospin-averaged baryons.

Two interesting observations, based on a study of the hadronic spectrum, lead to improved predictions for the b baryons. The first is that the effective mass of the constituent quark depends on the spectator quarks [6, 10], and the second is an effective supersymmetry [9] – a resemblance between mesons and baryons where the anti-quark is replaced by a diquark [11].

In this paper we extend the same methodology to obtain predictions for the masses of additional baryonic states containing the b quark that will be experimentally accessible in the foreseeable future.

2 Ω_b mass prediction

Table I: Hadron masses used in the calculation of the Ω_b mass prediction

Splitting	Value (MeV)
$M(\Omega_c)$	2697.5 ± 2.6
$M(\Omega_c^*)$	2768.3 ± 3.0
$M(\Omega_c^*) - M(\Omega_c)$	70.8 ± 1.5
$M(D_s)$	1968.49 ± 0.34
$M(D_s^*)$	2112.3 ± 0.5
$M(B_s)$	5366.1 ± 0.6
$M(B_s^*)$	5412.0 ± 1.2
$M(B_s^*) - M(B_s)$	45.9 ± 1.2
$M(\Xi_c^0)$	2471.0 ± 0.4
$M(\Xi_b^-)$	5792.9 ± 3.0

Taking the approach implemented in [10] for the prediction of the Ξ_b mass, the spin averaged mass of Ω_b can be obtained by extrapolation from available data for Ω_c and a correction based on strange meson masses, as listed in Table I:

$$\begin{aligned} M(\widetilde{\Omega_b}) &\equiv \frac{2M(\Omega_b^*) + M(\Omega_b)}{3} = \frac{2M(\Omega_c^*) + M(\Omega_c)}{3} + (m_b - m_c)_{B_s - D_s} \qquad (2) \\ &= \frac{2M(\Omega_c^*) + M(\Omega_c)}{3} + \frac{3M(B_s^*) + M(B_s)}{4} - \frac{3M(D_s^*) + M(D_s)}{4} \\ &= 6068.9 \pm 2.4 \text{ MeV} \end{aligned}$$

where $M(\widetilde{X})$ denotes the spin-averaged mass that cancels out the hyperfine interaction between the heavy quark and the diquark containing lighter quarks.

The HF splitting can be estimated as follows:

$$M(\Omega_b^*) - M(\Omega_b) = (M(\Omega_c^*) - M(\Omega_c))\frac{m_c}{m_b} = 24.0 \pm 0.7 \text{ MeV}, \qquad (3)$$

where we have used the experimental mass difference [13] $M(\Omega_c^*) - M(\Omega_c) = 70.8 \pm 1.0 \pm 1.1$ MeV $= 70.8 \pm 1.5$ MeV with m_b/m_c taken to be 2.95 ± 0.06, as discussed in the Appendix. This gives the following mass predictions:

$$\Omega_b^* = 6076.9 \pm 2.4 \text{ MeV}; \quad \Omega_\mathrm{b} = 6052.9 \pm 2.4 \text{ MeV} \qquad (4)$$

Taking into account the wavefunction correction as described in [12], one must add the following correction to the spin averaged mass:

$$\begin{aligned} v\left[\frac{\langle\delta(r_{ss})\rangle_{\Omega_b}}{m_s^2} - \frac{\langle\delta(r_{ss})\rangle_{\Omega_c}}{m_s^2}\right] &= v\frac{\langle\delta(r_{ss})\rangle_{\Omega_c}}{m_s^2}\left[\frac{\langle\delta(r_{ss})\rangle_{\Omega_b}}{\langle\delta(r_{ss})\rangle_{\Omega_c}} - 1\right] \\ &\approx (50 \pm 10)\left[\frac{\langle\delta(r_{ss})\rangle_{\Omega_b}}{\langle\delta(r_{ss})\rangle_{\Omega_c}} - 1\right] = 2.0 \pm 1.1 \text{ MeV} \qquad (5) \end{aligned}$$

where the contact probability ratio was computed using variational methods

$$\frac{\langle\delta(r_{ss})\rangle_{\Omega_b}}{\langle\delta(r_{ss})\rangle_{\Omega_c}} = 1.04 \pm 0.02 \ , \tag{6}$$

and we used the following calculation to evaluate the strength of the ss HF interaction:

$$\begin{aligned} 50 \text{ MeV} &\approx M(\Omega) + \frac{1}{4}(2M(\Xi_c^*) + M(\Xi_c') + M(\Xi_c)) \\ &\quad -\frac{1}{3}(2M(\Xi^*) + M(\Xi)) - \frac{1}{3}(2M(\Omega_c^*) + M(\Omega_c)) = \\ &= \left(3m_s + 3v\frac{\langle\delta(r_{ss})\rangle_\Omega}{m_s^2}\right) + \left(m_u + m_s + m_c\right) \\ &\quad -\left(2m_s + m_u + v\frac{\langle\delta(r_{ss})\rangle_\Xi}{m_s^2}\right) - \left(2m_s + m_c + v\frac{\langle\delta(r_{ss})\rangle_{\Omega_c}}{m_s^2}\right) \\ &\approx v\frac{\langle\delta(r_{ss})\rangle}{m_s^2} \end{aligned} \tag{7}$$

An alternate derivation of the Ω_b mass from the $\Xi_b - \Xi_c$ mass difference

Thanks to new measurements of the Ξ_b^- mass [2, 3], we now have another way of estimating the spin-averaged Ω_b mass. Following the approach in Ref. [10] the $\Xi_b^- - \Xi_c^0$ mass difference can be schematically written as

$$\begin{aligned} M(\Xi_b^-) - M(\Xi_c^0) &= (m_b - m_c) + (\text{wavefunction correction}) + (\text{EM correction}) \\ &= (m_b - m_c) + (-4 \pm 4)\ \text{MeV} + (V_{bsd}^{EM} - V_{csd}^{EM}) \end{aligned} \tag{8}$$

where the value of the wave function correction is taken from [10] and the last term denotes the EM interactions of the relevant quarks.

Similarly, the spin-averaged $\Omega_b - \Omega_c$ mass difference can be written as

$$\begin{aligned} M(\widetilde{\Omega_b}) - M(\widetilde{\Omega_c}) &= (m_b - m_c) + (\text{wavefunction correction}) + (\text{EM correction}) \\ &= (m_b - m_c) + (2.0 \pm 1.1)\ \text{MeV} + (V_{bss}^{EM} - V_{css}^{EM}) \end{aligned} \tag{9}$$

where the wave-function correction is given in Eq. (5).

Since the b and s quarks have the same charge, the EM contribution $V_{bss}^{EM} - V_{css}^{EM}$ to the $\Omega_b - \Omega_c$ mass difference is almost the same as the EM contribution $V_{bsd}^{EM} - V_{csd}^{EM}$ to the $\Xi_b^- - \Xi_c^0$ mass difference, modulo a negligible correction from the change in the mean radius of the relevant baryons. We then immediately obtain

$$M(\widetilde{\Omega_b}) - M(\widetilde{\Omega_c}) = M(\Xi_b^-) - M(\Xi_c^0) + (6.0 \pm 4.1)\ \text{MeV} \tag{10}$$

which leads to

$$M(\widetilde{\Omega_b}) = 6072.6 \pm 5.6 \text{ MeV} \tag{11}$$

to be compared with $M(\widetilde{\Omega_b}) = 6070.9 \pm 2.7$ MeV from Eqs. (2) and (5).

The consistency of these two estimates, based on different experimental inputs, is a strong indication that both the central values and the error estimates are reliable. Moreover, the estimate in Eq. (11) includes EM corrections, while the estimate Eqs. (2) does not, thus indicating that the EM corrections are likely to be smaller than our error estimate. Consequently, in the following we use the estimate (11).

Wave function correction to the hyperfine splitting

We must also compute the correction to the HF splitting

$$M(\Omega_b^*) - M(\Omega_b) \quad = \quad (M(\Omega_c^*) - M(\Omega_c))\frac{m_c}{m_b}\frac{\langle\delta(r_{bs})\rangle_{\Omega_b}}{\langle\delta(r_{cs})\rangle_{\Omega_c}} = 30.7 \pm 1.3 \text{ MeV} \tag{12}$$

where we used

$$\frac{\langle\delta(r_{bs})\rangle_{\Omega_b}}{\langle\delta(r_{cs})\rangle_{\Omega_c}} = 1.28 \pm 0.04 \ , \tag{13}$$

leading to the following predictions:

$$\Omega_b^* = 6082.8 \pm 5.6 \text{ MeV}; \quad \Omega_{\mathrm{b}} = 6052.1 \pm 5.6 \text{ MeV} \tag{14}$$

An alternative derivation of HF splitting from effective supersymmetry

An alternative approach to estimate the HF splitting is to use the effective meson-baryon supersymmetry discussed in [9] and apply it to the case of hadrons related by changing a strange antiquark $\bar{s}$ to a doubly strange ss diquark coupled to spin $S = 1$:

$$\begin{aligned} \frac{M(\Omega_b^*) - M(\Omega_b)}{M(B_s^*) - M(B_s)} \quad &= \quad \frac{M(\Omega_c^*) - M(\Omega_c)}{M(D_s^*) - M(D_s)} \quad = \quad \frac{M(\Xi^*) - M(\Xi)}{M(K^*) - M(K)} \\ &\approx \quad 0.49 \pm 0.01 \qquad \approx \quad 0.54 \end{aligned} \tag{15}$$

$$\Omega_b^* - \Omega_b = (B_s^* - B_s)(0.52 \pm 0.02) = 23.9 \pm 1.1 \text{ MeV} \tag{16}$$

This gives

$$\Omega_b^* = 6076.8 \pm 2.4 \text{ MeV}; \quad \Omega_{\mathrm{b}} = 6053.0 \pm 2.5 \text{ MeV} \ . \tag{17}$$

The main difference between these predictions and the ones given in the past [5, 7] is the use of masses of hadrons containing strange quarks [10], rather than Λ_b and Λ_c masses, to obtain the quark mass difference $m_b - m_c$. We also take into account wave function corrections which influence the hyperfine splitting between Ω_b^* and Ω_b. The net result is that we predict substantially lower masses for Ω_b than both Ref. [5]: $M(\Omega_b) = 6068.7 \pm 11.1$ MeV, and Ref. [7]: $M(\Omega_b) = 6065$ MeV. Our predicted hyperfine splitting $M(\Omega_b^*) - M(\Omega_b) = 30.7 \pm 1.3$ MeV (when wave function effects are included) is also larger than those of Refs. [5] (14.5 MeV) and [7] (23 MeV).

3 Ξ_b isospin splitting

The Ξ_b^0 mass is expected to be measured by the CDF collaboration through the channel $\Xi_b^0 \to \Xi_c^+ \pi^-$, where $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$, $\Xi^- \to \Lambda \pi^-$, and $\Lambda \to p\pi^-$ [14].

The source for the isospin splitting (ΔI) is the difference in the mass and charge of the u and d quarks. These differences affect the hadron mass in four ways [15]: they change the constituent quark masses ($\Delta M = m_d - m_u$), the Coulomb interaction (V^{EM}), and the spin-dependent interactions – both magnetic and chromo-magnetic (V^{spin}). One can obtain a prediction for the Ξ_b isospin splitting by extrapolation from the Ξ data, which has similar structure as far as EM interactions are concerned (note that for Ξ_b there are no spin-dependent interactions between the heavy quark and the su diquark which is coupled to spin zero):

$$\Delta I(\Xi^*) = \Delta M + \left[V^{EM}_{ssd} - V^{EM}_{ssu}\right] + 2\left[V^{spin}_{ds} - V^{spin}_{us}\right] = 3.20 \pm 0.68 \text{ MeV} \quad (18)$$

$$\Delta I(\Xi) = \Delta M + \left[V^{EM}_{ssd} - V^{EM}_{ssu}\right] - 4\left[V^{spin}_{ds} - V^{spin}_{us}\right] = 6.85 \pm 0.21 \text{ MeV} \quad (19)$$

$$\begin{aligned} \Rightarrow \Delta I(\Xi_b) &= \Delta M + \left[V^{EM}_{ssd} - V^{EM}_{ssu}\right] - 3\left[V^{spin}_{ds} - V^{spin}_{us}\right] \quad (20) \\ &= \frac{2\Delta I(\Xi^*) + \Delta I(\Xi)}{3} + \frac{\Delta I(\Xi) - \Delta I(\Xi^*)}{2} \\ &= \frac{\Delta I(\Xi^*) + 5\Delta I(\Xi)}{6} \\ &= 6.24 \pm 0.21 \text{ MeV} \end{aligned}$$

With the observed value [3] $M(\Xi_b^-) = (5792.9 \pm 2.5 \pm 1.7)$ MeV (the error from the D0 experiment is considerably larger [2]) and this estimate, we predict $M(\Xi_b^0) = 5786.7 \pm 3.0$ MeV.

Another option is to use Ξ_c, which has the same spin-dependent interactions, as a starting point:

$$\Delta I(\Xi_c) = \Delta M + \left[V^{EM}_{csd} - V^{EM}_{csu}\right] - 3\left[V^{spin}_{ds} - V^{spin}_{us}\right] = 3.1 \pm 0.5 \text{ MeV} \quad (21)$$

$$\begin{aligned} \Rightarrow \Delta I(\Xi_b) &= \Delta M + \left[V^{EM}_{ssd} - V^{EM}_{ssu}\right] - 3\left[V^{spin}_{ds} - V^{spin}_{us}\right] \quad (22) \\ &= \Delta I(\Xi_c) + \left[V^{EM}_{ssd} - V^{EM}_{ssu}\right] - \left[V^{EM}_{csd} - V^{EM}_{csu}\right] \\ &= \Delta I(\Xi_c) + \frac{2\Delta I(\Xi^*) + \Delta I(\Xi)}{3} - \frac{2\Delta I(\Xi_c^*) + \Delta I(\Xi_c') + \Delta I(\Xi_c)}{4} \\ &= 6.4 \pm 1.6 \text{ MeV} \end{aligned}$$

We summarize the isospin splittings which have been used in these calculations in Table II. All masses have been taken from the 2007 updated tables of the Particle Data Group [16], and all values of ΔI are defined as M(baryon with d quark) - M(baryon with u quark).

Table II: Isospin splittings ΔI used in calculating $\Delta I(\Xi_b) \equiv M(\Xi_b^-) - M(\Xi_b^0)$.

Splitting	Value (MeV)
$\Delta I(\Xi)$	6.85 ± 0.21
$\Delta I(\Xi^*)$	3.20 ± 0.68
$\Delta I(\Xi_c)$	3.1 ± 0.5
$\Delta I(\Xi_c')$	2.3 ± 4.24
$\Delta I(\Xi_c^*)$	-0.5 ± 1.84

4 Λ_b and Ξ_b orbital excitations

Table III: Masses of Λ and Ξ baryon ground states and orbital excitations [16].

	Λ	Λ_c	Ξ_c^+	Ξ_c^0
$M(1/2^+)$	1115.683 ± 0.006	2286.46 ± 0.14	2467.9 ± 0.4	2471.0 ± 0.4
$M(1/2^-)$	1406.5 ± 4.0	2595.4 ± 0.6	2789.2 ± 3.2	2791.9 ± 3.3
$M(3/2^-)$	1519.5 ± 1.0	2628.1 ± 0.6	2816.5 ± 1.2	2818.2 ± 2.1

In the heavy quark limit, the $(1/2^-)$ and $(3/2^-)$ Λ^* and Ξ^* excitations listed in Table III can be interpreted as a P-wave isospin-0 spinless diquark coupled to the heavy quark. Under this assumption, the difference between the spin averaged mass of the Λ^* baryons and the ground state Λ is only the orbital excitation energy of the diquark.

$$\begin{aligned}
\Delta E_L(\Lambda) \equiv \frac{2\Lambda^*_{[3/2]} + \Lambda^*_{[1/2]}}{3} - \Lambda &= 366.15 \pm 1.49 \text{ MeV} \\
\Delta E_L(\Lambda_c) \equiv \frac{2\Lambda^*_{c[3/2]} + \Lambda^*_{c[1/2]}}{3} - \Lambda_c &= 330.74 \pm 0.47 \text{ MeV} \\
\Delta E_L(\Xi_c) \equiv \frac{2\Xi^*_{c[3/2]} + \Xi^*_{c[1/2]}}{3} - \Xi_c &= 339.11 \pm 1.11 \text{ MeV}
\end{aligned} \tag{23}$$

The spin-orbit splitting seems to behave like $1/m_Q$:

$$\begin{aligned}
\Lambda^*_{[3/2]} - \Lambda^*_{[1/2]} &= 113.0 \pm 4.1 \text{ MeV} \\
\Lambda^*_{c[3/2]} - \Lambda^*_{c[1/2]} &= 32.7 \pm 0.8 \text{ MeV} \\
\Xi^*_{c[3/2]} - \Xi^*_{c[1/2]} &= 26.9 \pm 2.6 \text{ MeV}
\end{aligned} \tag{24}$$

where the Ξ_c entries are isospin averages.

The orbital excitation energies in Eq. (23) may be extrapolated to the case of excited Λ_b baryons in the following manner. Energy spacings in a power-law potential $V(r) \sim r^\nu$ behave with reduced mass μ as $\Delta E \sim \mu^p$, where $p = -\nu/(2+\nu)$ [17]. For light quarks in the confinement regime, one expects $\nu = 1$ and $p = -1/3$, while for the

$c\bar{c}$ and $b\bar{b}$ quarkonium states, with nearly equal level spacings, an effective power is $\nu \simeq 0$ and $p \simeq 0$. One should thus expect orbital excitations to scale with some power $-1/3 \leq p \leq 0$. One can narrow this range by comparing the Λ and Λ_c excitation energies and estimating p with the help of reduced masses μ for the Λ and Λ_c.

$$\frac{\mu(\Lambda_c)}{\mu(\Lambda)} = \frac{M[ud]\ m_c}{M[ud]+m_c}\frac{M[ud]+m_s}{M[ud]\ m_s} = \frac{M(\Lambda)}{M(\Lambda_c)}\frac{m_c}{m_s} = 1.55 \tag{25}$$

Now we use the ratio $\Delta E_L(\Lambda_c)/\Delta E_L(\Lambda) = 0.903 \pm 0.004$ to extract an effective power $p = -0.23 \pm 0.01$ which will be used to extrapolate to the Λ_b system:

$$\begin{aligned} \Delta E_L(\Lambda_b) &= \Delta E_L(\Lambda_c)\left[\frac{\mu(\Lambda_b)}{\mu(\Lambda_c)}\right]^p = \Delta E_L(\Lambda_c)\left[\frac{M(\Lambda_c)}{M(\Lambda_b)}\frac{m_b}{m_c}\right]^p \\ &= \Delta E_L(\Lambda_c)\left[\frac{M(\Lambda_c)[M(\Lambda_b)-M(\Lambda)+m_s]}{M(\Lambda_b)[M(\Lambda_c)-M(\Lambda)+m_s]}\right]^p \\ &= \Delta E_L(\Lambda_c)\left[\frac{1-\dfrac{M(\Lambda)-m_s}{M(\Lambda_b)}}{1-\dfrac{M(\Lambda)-m_s}{M(\Lambda_c)}}\right]^p = 317 \pm 1 \text{ MeV} \end{aligned} \tag{26}$$

where the last form of the expression shows the explicit dependence of the result on m_s. Using the value $M(\Lambda_b) = (5619.7 \pm 1.2 \pm 1.2)$ MeV observed by the CDF Collaboration [19], and rescaling the fine-structure splittings of Eq. (24) by $1/m_Q$ with $m_b/m_c = 2.95 \pm 0.06$, we find

$$M(\Lambda^*_{b[3/2]}) - M(\Lambda^*_{b[1/2]}) = \frac{m_c}{m_b}(M(\Lambda^*_{c[3/2]}) - M(\Lambda^*_{c[1/2]})) = (11.1 \pm 0.4) \text{ MeV} \ , \tag{27}$$

$$M(\Lambda^*_{b[1/2]}) = (5929 \pm 2) \text{ MeV} \ , \quad M(\Lambda^*_{b[3/2]}) = (5940 \pm 2) \text{ MeV} \ . \tag{28}$$

The observed values of the Σ_b masses [1],

$$\begin{aligned} M(\Sigma_b^-) &= 5815.2 \pm 1.0(\text{stat.}) \pm 1.7(\text{syst.}) \text{ MeV} \\ M(\Sigma_b^+) &= 5807.8\,^{+2.0}_{-2.2}\,(\text{stat.}) \pm 1.7(\text{syst.}) \text{ MeV} \end{aligned} \tag{29}$$

are sufficiently close to the predicted values of $M(\Lambda^*_{b[1/2,3/2]})$ that the decays $\Lambda^*_{b[1/2,3/2]} \to \Sigma_b^{\pm}\pi^{\mp}$ are forbidden. The $\Lambda^*_{b[1/2,3/2]}$ should decay directly to $\Lambda_b\pi^+\pi^-$.

A similar calculation may be performed for the orbitally-excited Ξ_b states. Here, to a good approximation [10], one may regard the $[sd]$ diquark in Ξ_b^- or the $[su]$ diquark in Ξ_b^0 as having spin zero, so that methods similar to those applied for excited Λ_b states should be satisfactory. We find

$$\Delta E_L(\Xi_b) = \Delta E_L(\Xi_c)\left[\frac{\mu(\Xi_b)}{\mu(\Xi_c)}\right]^p = \Delta E_L(\Xi_c)\left[\frac{M(\Xi_c)}{M(\Xi_b)}\frac{m_b}{m_c}\right]^p = (322 \pm 2) \text{ MeV} \ . \tag{30}$$

Now we use the observed Ξ_b^- mass [3] $M(\Xi_b^-) = (5792.9 \pm 2.5 \pm 1.7)$ MeV and our estimate of isospin splitting $M(\Xi_b^-) - M(\Xi_b^0) = 6.4 \pm 1.6$ MeV to predict the isospin-averaged value $M(\Xi_b) = 5790 \pm 3$ MeV. We then rescale the fine-structure splitting (24) and find

$$\Xi^*_{b[3/2]} - \Xi^*_{b[1/2]} = \frac{m_c}{m_b}(\Xi^*_{c[3/2]} - \Xi^*_{c[1/2]}) = (9.1 \pm 0.9) \text{ MeV} , \tag{31}$$

$$M(\Xi^*_{b[1/2]}) = (6106 \pm 4) \text{ MeV} , \quad M(\Xi^*_{b[3/2]}) = (6115 \pm 4) \text{ MeV} . \tag{32}$$

The lower state decays to $\Xi_b\pi$ via an S-wave, while the higher state decays to $\Xi_b\pi$ via a D-wave, and hence should be narrower. Decays to $\Xi_b'\pi$ and $\Xi_b^*\pi$ also appear to be just barely allowed, given the values of $M(\Xi_b', \Xi_b^*)$ predicted in Ref. [10].

5 Conclusions

We have predicted the masses of several baryons containing b quarks, using descriptions of the color hyperfine interaction which have proved successful for earlier predictions. Correcting for wave function effects, we find $M(\Omega_b) = 6052.1 \pm 5.6$ MeV and $M(\Omega_b^*) = 6082.8 \pm 5.6$ MeV. These values are below others which have appeared in the literature as a result of our use of hadrons containing strange quarks to evaluate the effective $b-c$ mass difference, the inclusion of electromagnetic contributions, and because of a different hyperfine splitting.

We have evaluated the isospin splitting of the Ξ_b states and find $\Delta I(\Xi_b) \equiv M(\Xi_b^-) - M(\Xi_b^0) = 6.24 \pm 0.21$ MeV on the basis of an extrapolation from the Ξ and Ξ^* states. This value is consistent with one which includes information from the Ξ_c states, $\Delta I(\Xi_b) = 6.4 \pm 1.6$ MeV.

We have also evaluated the orbital excitation energy for Λ_b and Ξ_b states in which the light diquark (ud or us) remains in a state of $L = S = 0$. Precise predictions have been given for the masses of the states $\Lambda^*_{b[1/2,3/2]}$ and $\Xi^*_{b[1/2,3/2]}$.

Our predictions are summarized in Table IV. We look forward to further experimental progress in the tests of these predictions.

Table IV: Summary of predictions for b baryons

	Mass in MeV
$M(\Omega_b)$	6052.1 ± 5.6
$M(\Omega_b^*)$	6082.8 ± 5.6
$M(\Xi_b^0)$	5786.7 ± 3.0
$M(\Lambda^*_{b[1/2]})$	5929 ± 2
$M(\Lambda^*_{b[3/2]})$	5940 ± 2
$M(\Xi^*_{b[1/2]})$	6106 ± 4
$M(\Xi^*_{b[3/2]})$	6115 ± 4

Appendix: Values of quark masses

In choosing values for the quark masses used in this paper, we note that values of quark mass differences can be taken from the difference in masses of baryons containing spin-zero ud diquarks

$$m_i - m_j = M(\Lambda_i) - M(\Lambda_j) \tag{33}$$

where i and j can be b, c or s. This gives

$$\begin{aligned} m_c &= M(\Lambda_c) - M(\Lambda) + m_s = (2286.5 - 1115.68 + 538) \text{ MeV} = 1709 \text{ MeV} \\ m_b &= M(\Lambda_b) - M(\Lambda_c) + m_c \pm 10 \text{ MeV} = M(\Lambda_b) - M(\Lambda) + m_s \pm 10 \text{ MeV} \\ &= 5619.7 - 1115.68 + 538 \pm 10 \text{ MeV} = 5042 \pm 10 \text{ MeV} \end{aligned} \tag{34}$$

where $m_s = 538$ MeV has been taken from the fit of Ref. [18] to light-quark baryon spectra.

We have noted [6] that an uncertainty of 10 MeV arises from the difference between the values of $m_b - m_c$ obtained from hadrons having strange and nonstrange spectators. We have chosen the value obtained from strange spectators following its use in previous successful predictions [10].

Although this difference is crucial in predictions like Eq. (2) which depend on mass differences, its effect on mass ratios is negligible. We therefore use the values obtained from baryons with nonstrange spectators to obtain a value for the mass ratio m_b/m_c.

$$\frac{m_b}{m_c} = \frac{[M(\Lambda_b) - M(\Lambda) + m_s + \delta m]}{[M(\Lambda_c) - M(\Lambda) + m_s + \delta m]} = \frac{5042 + \delta m}{1709 + \delta m} \approx 2.95 - \frac{\delta m}{876 \text{ MeV}} \ , \tag{35}$$

where we have introduced the quantity δm to take care of any errors in the assumption that $m_s = 538$ MeV and neglected the 10 MeV uncertainty in m_b. Taking $\delta m = \pm 50$ MeV in the calculation of m_b/m_c gives the value $m_b/m_c = 2.95 \pm 0.06$ used in the Ω_b mass prediction.

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References

[1] T. Aaltonen *et al.* [CDF Collaboration], [arXiv:hep-ex/0706.3868].

[2] V. Abazov *et al.* [D0 Collaboration], [arXiv:hep-ex/0706.1690], Phys. Rev. Lett. **99**, 052001 (2007).

[3] T. Aaltonen *et al.* [CDF Collaboration], [arXiv:hep-ex/0707.0589], Phys. Rev. Lett. **99**, 052002 (2007).

[4] E. Bagan, M. Chabab, H. G. Dosch and S. Narison, Phys. Lett. B **278**, 367 (1992); B **287**, 176 (1992); S. Capstick and N. Isgur, Phys. Rev. D **34**, 2809 (1986);

N. Mathur, R. Lewis and R. M. Woloshyn, Phys. Rev. D **66**, 014502 (2002).

[5] E. Jenkins, Phys. Rev. D **54**, 4515 (1996); *ibid.* **55**, 10 (1997).

[6] M. Karliner and H. J. Lipkin, [arXiv:hep-ph/0307243] (unpublished).

[7] D. Ebert, R. N. Faustov and V. O. Galkin, Phys. Rev. D **72**, 034026 (2005).

[8] J. L. Rosner, Phys. Rev. D **75**, 013009 (2007) [arXiv:hep-ph/0611207].

[9] M. Karliner and H. J. Lipkin, [arXiv:hep-ph/0611306].

[10] M. Karliner, B. Keren-Zur, H. J. Lipkin and J. L. Rosner, [arXiv:hep-ph/0706.2163].

[11] D. B. Lichtenberg, J. Phys. G **16**, 1599 (1990); J. Phys. G **19** (1993) 1257; D. B. Lichtenberg, R. Roncaglia and E. Predazzi, J. Phys. G **23** (1997) 865.

[12] B. Keren-Zur, Ann. Phys. in press, `http://dx.doi.org/10.1016/j.aop.2007.04.010`, [arXiv:hep-ph/0703011].

[13] B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **97**, 232001 (2006).

[14] D. Litvintsev [for the CDF Collaboration], seminar at Fermilab, June 15, 2007/

[15] J. L. Rosner, Phys. Rev. D **57**, 4310 (1998) [arXiv:hep-ph/9707473].

[16] Particle Data Group, `http://pdg.lbl.gov/2007/listings/contents_listings.html`

[17] C. Quigg and J. L. Rosner, Phys. Lett. B **71**, 153 (1977).

[18] S. Gasiorowicz and J. L. Rosner, Am. J. Phys. **49**, 954 (1981).

[19] D. Acosta *et al.* [CDF Collaboration], Phys. Rev. Lett. **96**, 202001 (2006) [arXiv:hep-ex/0508022].